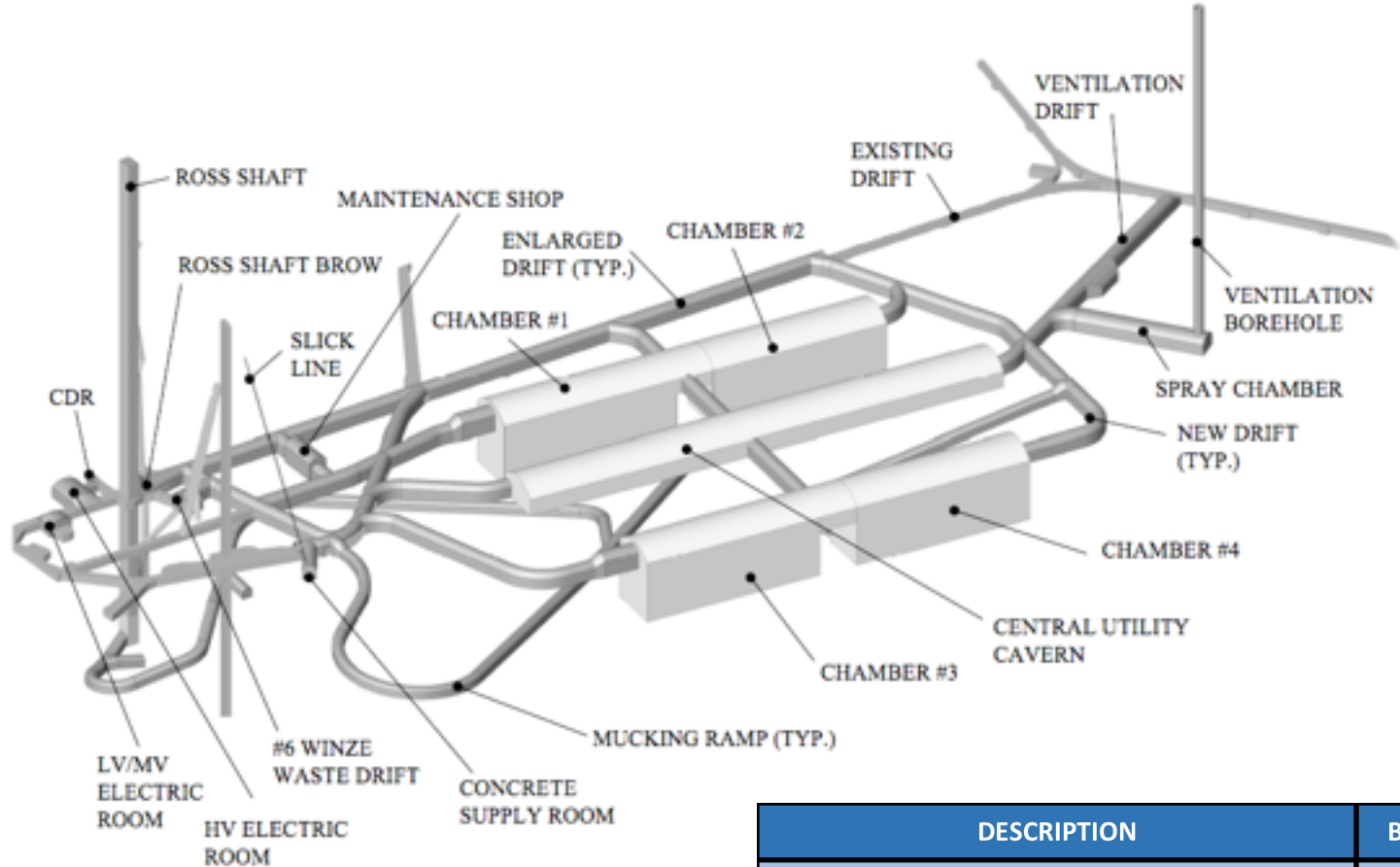


Summary of Scientific Requirements, Detector Performance Numbers, Improvements.

Milind Diwan
(with lots of help)
BNL
Date: Dec 8, 2015

Some good news



Closeout report posted: recommendation to proceed to CD3a

\$M	FY17	FY18	FY19	FY20	FY21	TOTAL
CD-3a Obligations	15	42	80	75	7	219
CD-3a Contingency	6	16	30	28	3	83
Total	21	58	110	103	10	302

DESCRIPTION	BCWS (\$M)
Far Site Conventional Facilities Construction	219
FSCF Construction Management	26
Pre-Excavation (Pre-EXC)	49
Cavern & Drift Excavation (EXC)	102
Buildings & Site Infrastructure (BSI)	42
Contingency need	83
CD-3A TOTAL REQUEST	302

Some perspective

PROJECT STATUS as of 10/2015		
Project Type	Line Item	
CD-1	1Q/2013	10-Dec-2012 (A)
CD-1R	1Q/2016	5-Nov-2015 (A)
CD-3a	2Q/2017	
CD-3b	2Q/2020	
CD-2/ 3c	1Q/2021	
CD-4	4Q/2030	
TPC Percent Complete	10%	10%
TPC Cost to Date	\$108M	
TPC Committed to Date	\$112M	
TPC	\$1,457M	
TEC	\$1,359M	
Contingency Cost (w/Mgmt Reserve)	\$342M	34%
Contingency Schedule on CD-4	40 months	29%
CPI Cumulative	N/A	
SPI Cumulative	N/A	

Outline of this talk

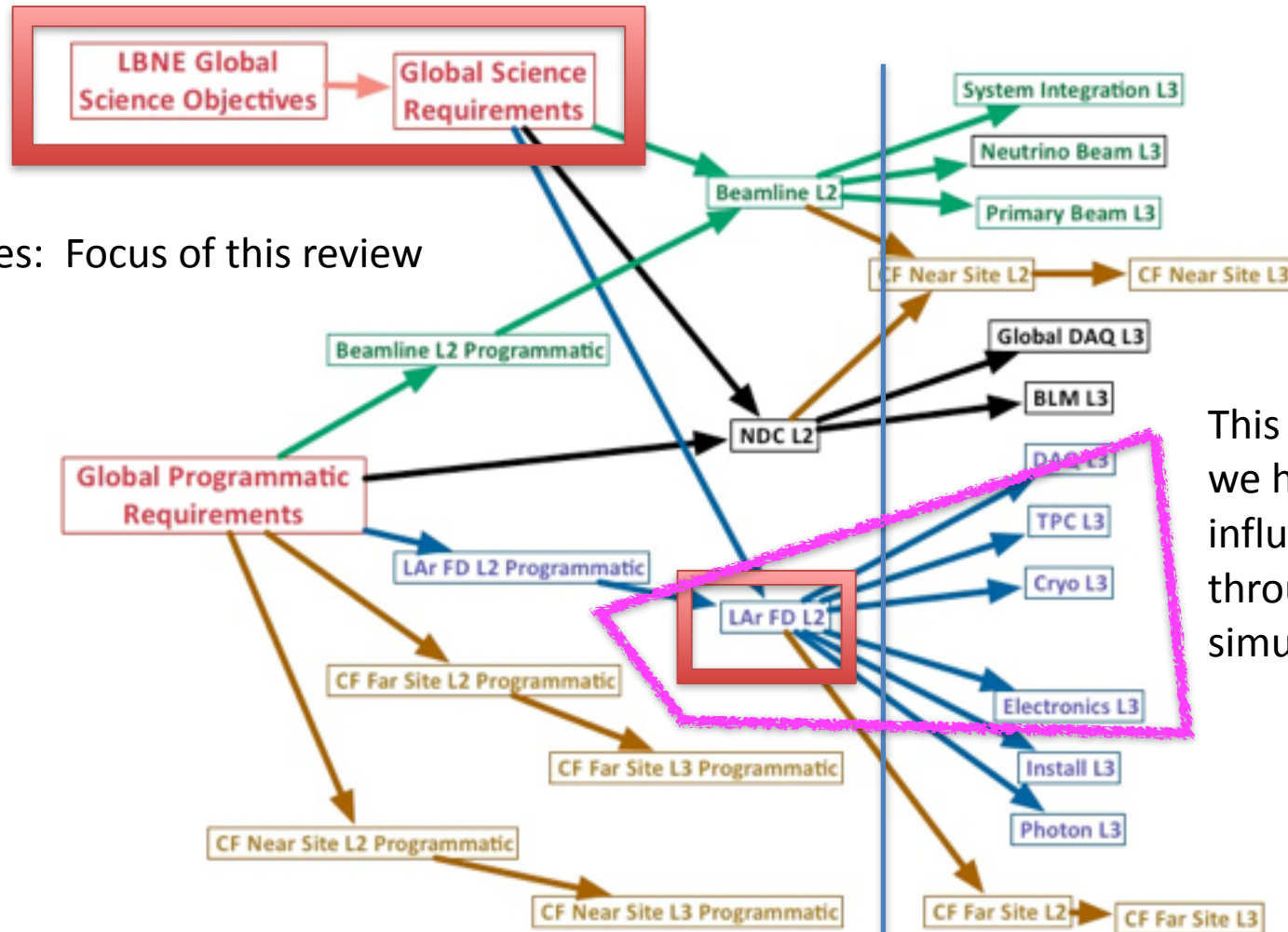
- Requirements development
- Documentation status
- Examples of key scientific requirements for far detector
 - Physics signals and backgrounds
 - Size/modularity
 - Location
 - Depth
 - Granularity
 - Technology (cryogenics, purity, and electronics)
 - Configuration choices
- What we need to pay attention to.
- We should figure out which parameters to focus on.

Requirements Status. This is a bit bureaucratic, but it can be helpful

- Requirements are **organized in cascading levels** starting with the scientific objectives.
- Requirements are stated even if a technical implementation is unknown. This allows notification of unmet requirements.
- High level requirements are **numerical only if the the parameter is fixed and affects all systems: i.e. The Single Turn Extraction (9.6 microsec)**
- **Each level becomes more focused and specific** on subsystems and design parameters and refers back so that design can be tracked back to scientific objectives.
- Complete set of draft requirements down to Level 2 exists.
- Interface documentation (with cryo and Civil) is in progress (Please see talks by Rucinsky).
- Level 3 and Level 4 start on design specifications which are partly complete and are also in the CDR narrative.
- Design parameters are in the CDR documentation.
- Please see DOCDDB-112
- Parameter sheet also in DOCDDB-112

Requirements Cascade and linked documentation.

Red boxes: Focus of this review



This is where we have to influence through simulations

Draft Complete/Interfaces identified See Rucinsky talk

Work in progress

Top Level Science Objectives

- Precision measurements in both Near and Far detectors which are necessary to determine the parameters that govern $\nu_\mu \rightarrow \nu_e$ (muon-neutrino to electron-neutrino) appearance, and similarly, $\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e$ appearance.
- Precision measurements in both Near and Far detectors which are necessary to determine the parameters that govern the muon neutrino and muon antineutrino disappearance channels
- A search for proton decay in the far detector, yielding a significant improvement in current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g. $p \rightarrow K^+ \nu$ or $p \rightarrow e^+ \pi^0$.
- Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of DUNE.

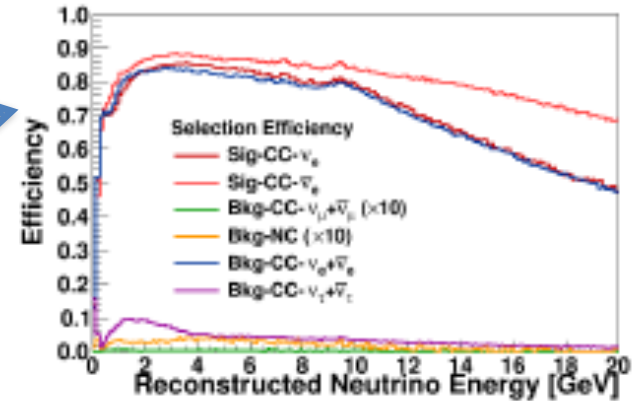
Global Science Requirements on Far detector.

- Far detector shall be capable of identifying electron neutrino and anti-neutrino charged current beam events in sufficient numbers within the fiducial volume of the detector. The neutrino flavor of the event will be identified by clearly identifying the primary final state charged electron. (similar for Muon Neutrinos)
- Far detector shall be capable of measuring the total energy of the charged current neutrino events.
- Far detector shall be capable of identifying events with multiple electromagnetic showers and non-showering particles produced within the fiducial volume of the detector.
- These choices lead to a high granularity far detector design choice to obtain high efficiency for accelerator electron neutrino events.
 - The far detector shall use liquid argon time projection chamber as the neutrino interactions target. (LAR)
 - The ν_μ and ν_e charged current interaction shall be identified with high efficiency regardless of the exclusive final state.
 - The detector shall distinguish a Minimum Ionizing Particle (MIP) track cleanly from electronic noise everywhere within the drift volume.

Key high level physics performance table

Table 4.2: Estimated range of the LArTPC detector performance parameters for the primary oscillation physics. Signal efficiencies, background levels, and resolutions are obtained from ICARUS and earlier simulation efforts (middle column) and the value chosen for the baseline LBNE neutrino oscillation sensitivity calculations (right column).

Parameter	Range of Values	Value Chosen For ν_e -CC
ν_e -CC efficiency	70-95%	
ν_μ -NC misidentification rate	0.4-2.0%	
ν_μ -CC misidentification rate	0.5-2.0%	
Other background	0%	
Signal normalization error	1-5%	
Background normalization error	2-15%	
For ν_μ -CC		
ν_μ -CC efficiency	80-95%	
ν_μ -NC misidentification rate	0.5-10%	
Other background	0%	
Signal normalization error	1-10%	
Background normalization error	2-20%	
For ν -NC		
ν -NC efficiency	70-95%	
ν_μ -CC misidentification rate	2-10%	
ν_e -CC misidentification rate	1-10%	
Other background	0%	
Signal normalization error	1-5%	
Background normalization error	2-10%	
Neutrino Energy Resolution		
ν_e -CC energy resolution	$15\%/\sqrt{E(\text{GeV})}$	
ν_μ -CC energy resolution	$20\%/\sqrt{E(\text{GeV})}$	
E_{ν_e} scale uncertainty	under study	
E_{ν_μ} scale uncertainty	1-5%	



This performance has been studied using fast monte carlo. The plot from CDR.

A new implementation of the sensitivity calculations take energy dependence and correlations of these parameters into account.

The performance leads to high granularity (<5 mm scale) detector with high efficiency for MIP, e/Gamma separation and excellent EM energy resolution.

Key Detector Performance Features Needed To Achieve Physics Performance

Table 4.1: **(PRELIMINARY)** Summary of the most important performance parameters of the DUNE reference far detector. Included are the parameters, previous detector performance, and projected performance with references to relevant studies. Notes: ¹For a MIP at the CPA, minimum in all three views, for any track angle; ²Achieved for the collection view; ³In order for the fiducial volume to be known to $\pm 1\%$; ⁴For a sample of stopping muons; ⁵For electron stubs with $E > 5$ MeV.

Parameter	Reference Performance	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio ¹	9:1	10:1 [1, 2] ²	9:1
Electron Lifetime	3 ms	> 15 ms [2]	> 3 ms
Uncertainty on Charge Loss due to Lifetime	< 1%	< 1% [2]	< 1%
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution ³	(2.5, 2.5, 2.5) cm		(0.5, 0.8, 2.0) cm [3, 4]
$e - \gamma$ separation ϵ_e	0.9		0.9
$e - \gamma$ separation γ rejection	0.99		0.99
Multiple Scattering Resolution on muon momentum ⁴	$\sim 18\%$	$\sim 18\%$ [5, 6]	$\sim 18\%$
Electron Energy Scale Uncertainty	5%	2.2% [7]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\text{MeV})}$ @1%	$0.33/\sqrt{E(\text{MeV})}$ [7] +1%	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	1–5%		From LArIAT and CERN Prototype
Stub-Finding Efficiency ⁵	90%		> 90%

S/N ratio applies to all 3 views. S/N, e-lifetime, dynamic range, resolution, and the sampling rate are all coupled parameters.

See Xin Qian's talk
Multitrack efficiency and shower reconstruction requires 3 wire views in combination with charge measurement.

Reconstruction effort is underway and may affect detailed design.

TPC Detector Configuration

Technical requirements

- 3 wire views to reconstruct showers and MIP, multitracks with high efficiency.
- Minimize wire length for S/N ratio. < 10 m
- Wire orientation to allow unique crossing solution.
- Cavern span \sim height < 25 m
- Wire pitch < 5 mm for S/N
- APA size < 2.5 m, Drift ~ 3.6 m

Other requirements

- Minimize work underground
- Design to facilitate laboratory testing
- Facilitate over the road transportation
- Facilitate down-the-shaft transport (Yates shaft)
- Maximize sensitive mass in cryostat.

Design choice: ACACA configuration with 2.3mX6m APA, wrapped X, U, V wires. U and V wires at ± 35.7 deg (only one X-ing per x-u, x-v pair). Pitch 4.79 mm provides 28000 electron/MIP over ENC < 600 e. Lifetime ~ 3 ms to get SNR from 3.6m ($O_2 < 0.1$ ppb)

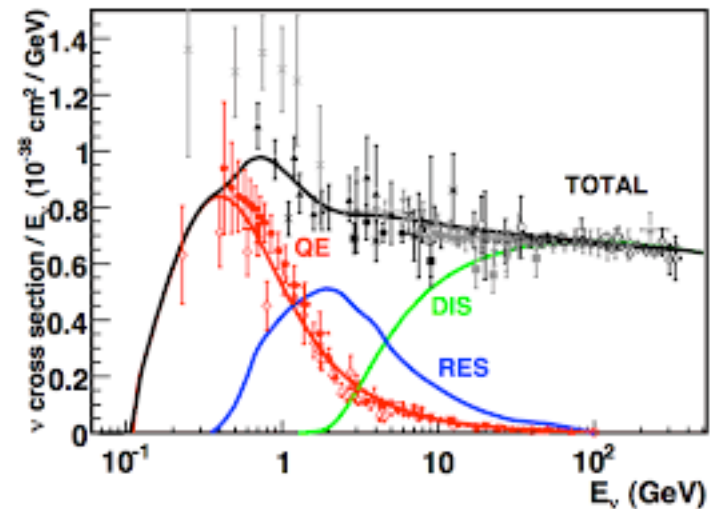
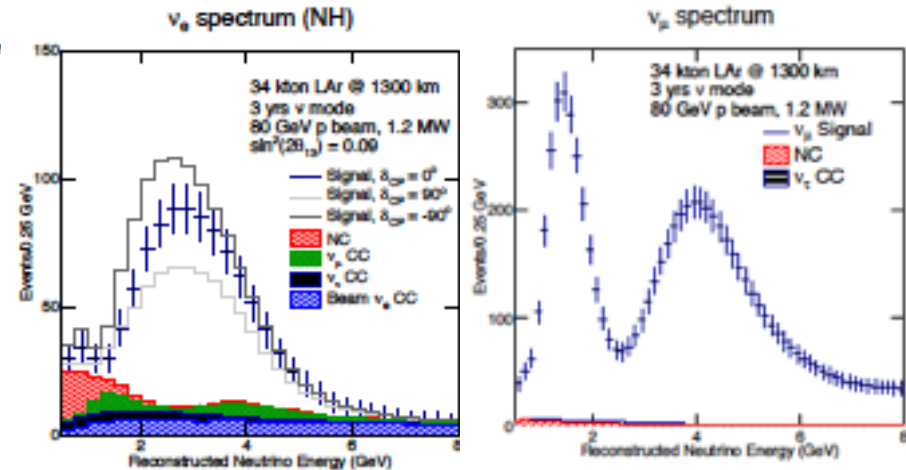
Parameter	Value	Unit	Status	L2 requirement
Nom. Fiducial	10	kt	***	Larfd--27, Actuals (11.6 fid, 17.1 total) =>osc statistics and modularity.
Depth	4850ft	Level	***	Larfd-95 => cosmic muons back => proton decay, supernova =
Dimension	2HX3WX25L	mods	***	larfd-27 => Modularity => construction => transport
Cosmic muons	<0.1	Hz	**	Calculation using dimensions and muon Monte Carlo.
Drift	3.6	m	***	Larfd-99 => electron lifetime => S/N needed => MIP efficiency
APA dim	2.3 X 6	m	***	Larfd-27=> Modularity => constructability => ability transport +> reduce wire length.
x, u, v wire spacing	4.79, 4.667, 4.667	mm	***	Larfd96 => high efficiency for reconstruction => CP physics.
Arrangement	ACACA		***	Cryo-30 => Maximum sensitive mass => larfd-99
Cryo dims	15.1X62x14	m	***	Cryo-26 => must accommodate TPC
Operating press	130	mbarg	**	Cryo-10 => Stability Cryo-23=> safety, Range 30 to 200mbarg
Drift field	500	v/cm	***	Larfd-99 => sufficient signal (charge/light) , uniformity, uptime
Drift time	2.25	ms	***	Calculation from drift distance and chosen E-field.
ENC @ 90k	<600	Elec	***	Larfd-7, Larfd-43 => MIP measurement with high efficiency Measurement is 550 electron @ 150 pf. From BNL.
Ionization (normal inc)	~28000	E/MIP	**	Calculation @ APA using 2.1 MeV/cm MIP and wire pitch.
S/N min in all Fid.	>9		***	Larfd-7, larfd-43, => MIP measurement with high effi.
ADC resolution min	11		***	Larfd-43, larfd-63 => resolution, dynamic range for PID.
ADC sampling	2	MHZ	***	Larfd-104, larfd-82 => measure drift coordinate with high eff.
E lifetime min	3	ms	**	Larfd-44 => obtain high MIP efficiency from the farthest point, Lar-98 => SN energy resolution.
Photon yield	0.1	PE/MeV	**	Larfd-28 => Ability to trigger @ 88 % eff. at 200 MeV visible energy
Photon time	1	Micro-sec	*	larfd-28=> larfd-82 => Proton decay larfd-29=> larfd83 => SN resolu
Readout	Continuous with zero suppression		**	Larfd-111 => continuous operation for SN detection. (not for beam)
Covers	10 (W) x 17 (h) x 62 L	m	***	Cryo-26 => Must accommodate TPC

That is a lot of information, what should we focus on ?

- Constraints and Parameters that drive the design
 - We must be able to use events with many tracks and showers. i.e. if an event has multiple EM showers, each must be tested if it is a photon or electron to achieve 80% efficiency for CC events. This should set the granularity.
 - Orientation of the event (or beam) with respect to the detector matters.
 - Liquid argon achievable purity provides the size of signal.
 - Achievable High voltage.
 - Electronic noise and expected performance.
 - Maximum possible APA dimensions.
 - Practical issues regarding packaging of electronics on the APA. (one side only in increments of 128 chan.)

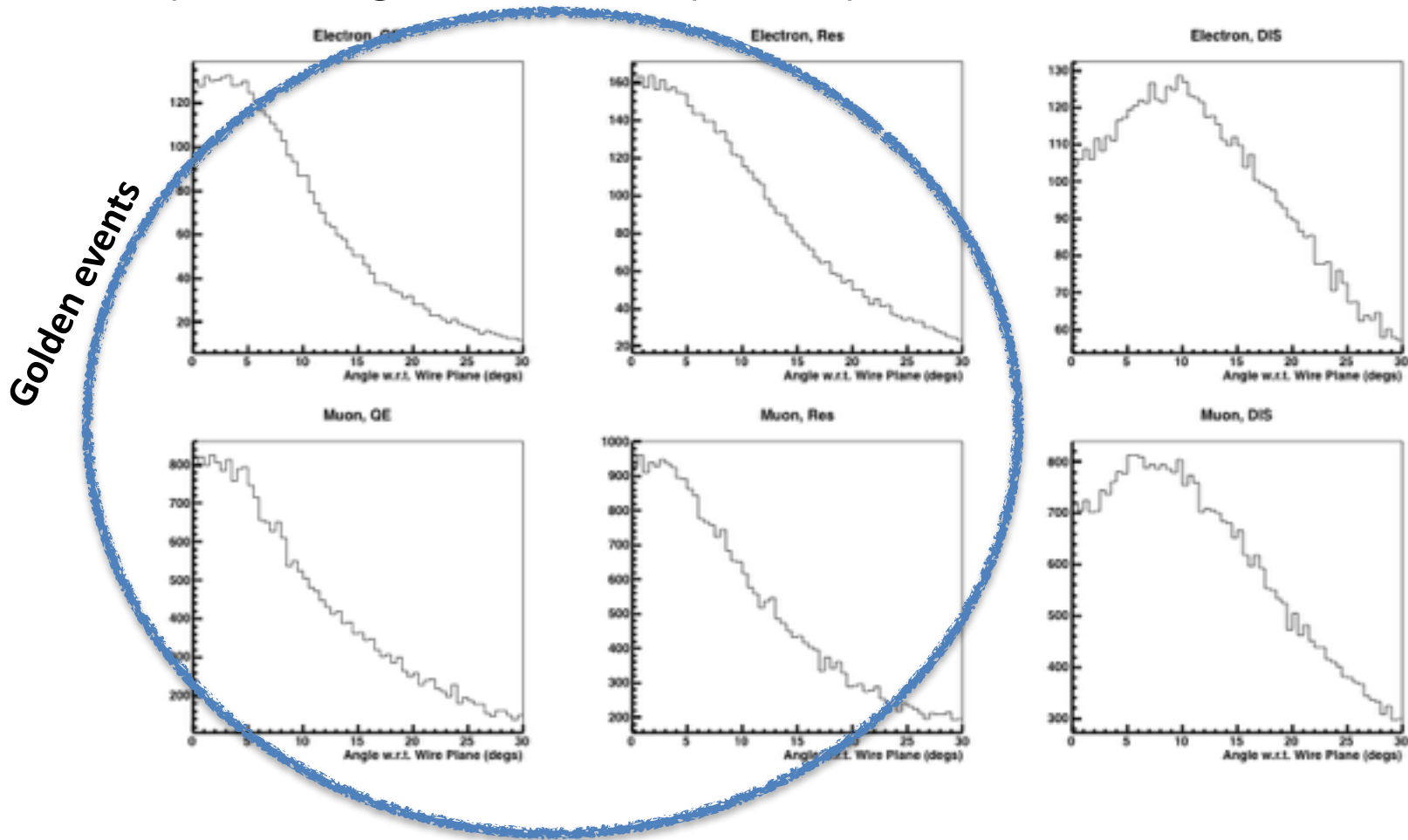
Event Characteristics

- Mean energy of events ~ 3 GeV.
- Average number of charge tracks ~ 4 -5
- Average number of photon showers ~ 2
- Protons and Neutrons ~ 2 (inconsistent MC)
- Number of π^0 should be twice charged π production.



Need to settle on this picture.

Lepton Angle with wire plane parallel



This is all signal. What efficiency can be achieved ?
We must not lose any of the golden events which are about $\sim 1/4$ of the total.

Geometry is important: Some history

- Tracking detectors have had similar issues with background suppression and analysis in the past.

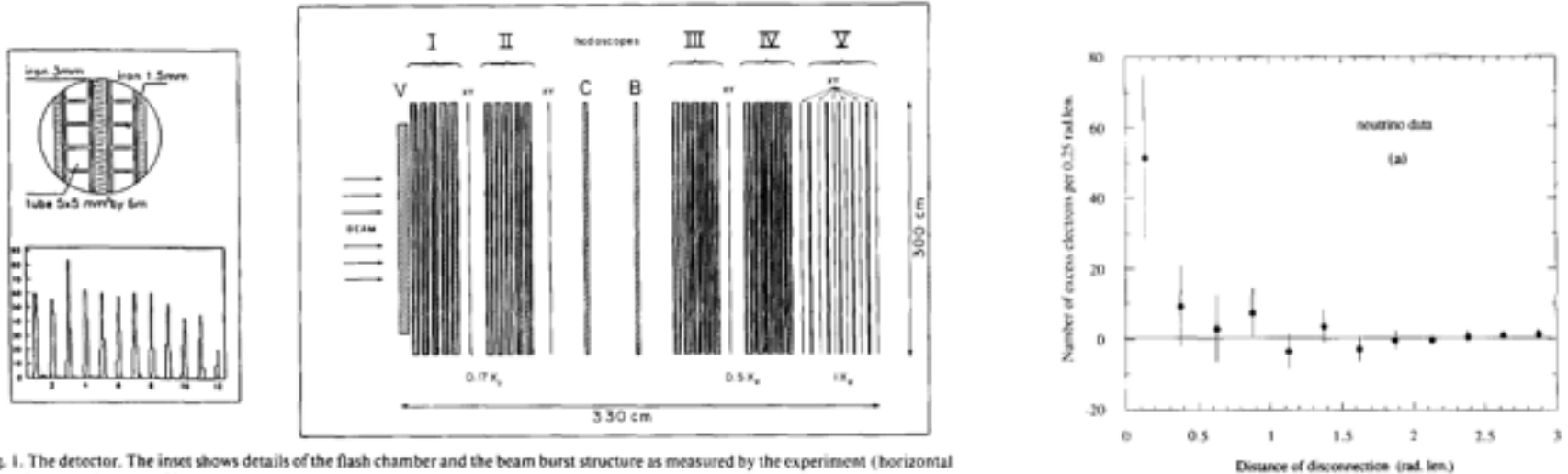


Fig. 1. The detector. The inset shows details of the flash chamber and the beam burst structure as measured by the experiment (horizontal scale gives time in units of 224 ns).

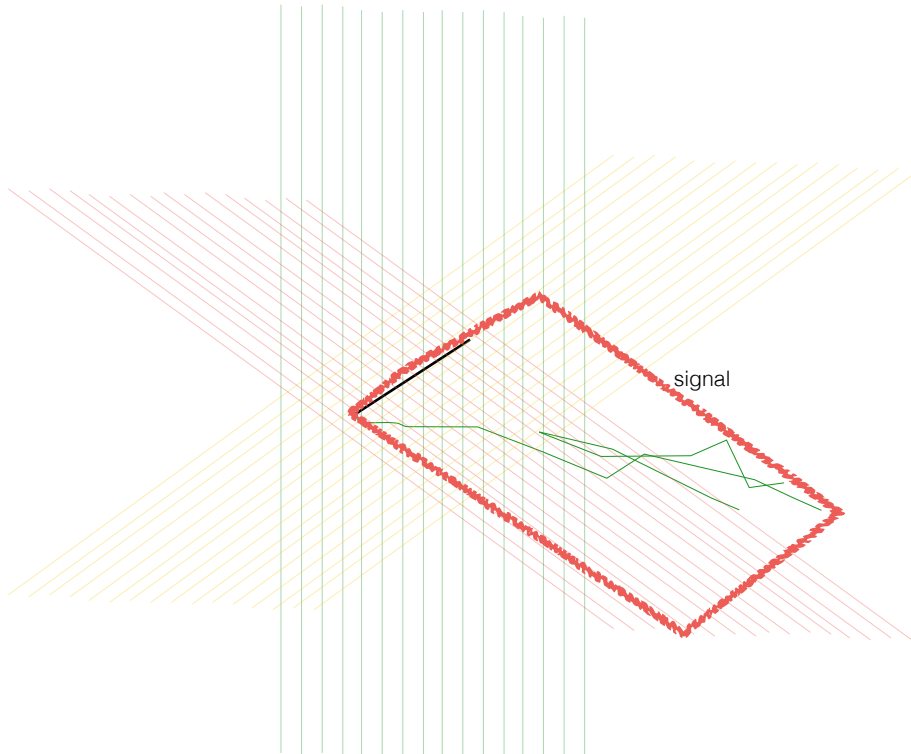
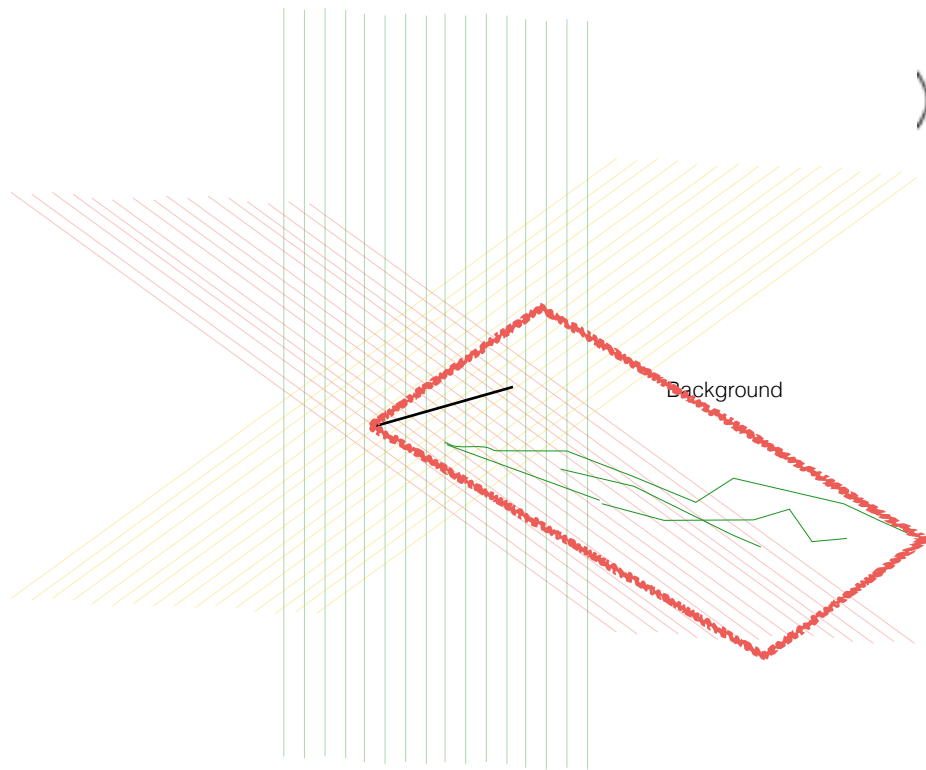
AGS-816 had only 1 view

ref: CERN-EP-89-128,

Search for Neutrino Oscillations P. Astier et al., Jan 1989. 18 pp.
Published in Phys.Lett. B220 (1989) 646

**A signal was found and
later dismissed as an
artifact of geometry**

Focus only on the golden events first. These have a single shower with a recoiling nucleon(s)



Two essential cuts for background suppression

- 1) Gap
- 2) dE/dx

These do not work well if the event is in the vertical plane. The entire event need not be in the vertical plane. Only the first few cm are important.

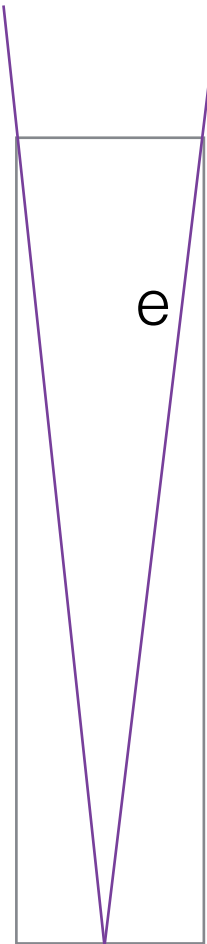
rad length ~ 14 cm.

Photon mean path $\sim 9/7 * 14 = 18$ cm

drift $v \sim 1.6$ mm/microsec.

Require that the gap for 90% of single photon conversions be visible. \Rightarrow gaps of >1.8 cm must be caught.

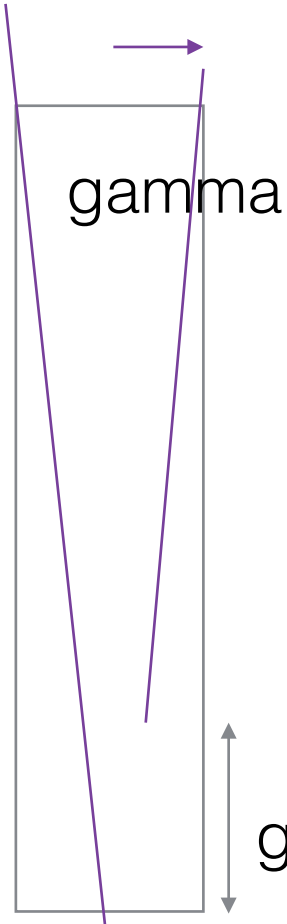
recoil



θ



gamma



g

drift



For $g > 2p$

$$g^* \theta > V^* dT$$

$$V = 1.6 \text{ mm}/\mu\text{s}$$

$$dT = 2 \mu\text{s}$$

$$p = 0.5 \text{ cm}$$

$$\Rightarrow \theta \sim 0.3$$

$$\sim 17 \text{ deg}$$

p



$$V^* dt$$

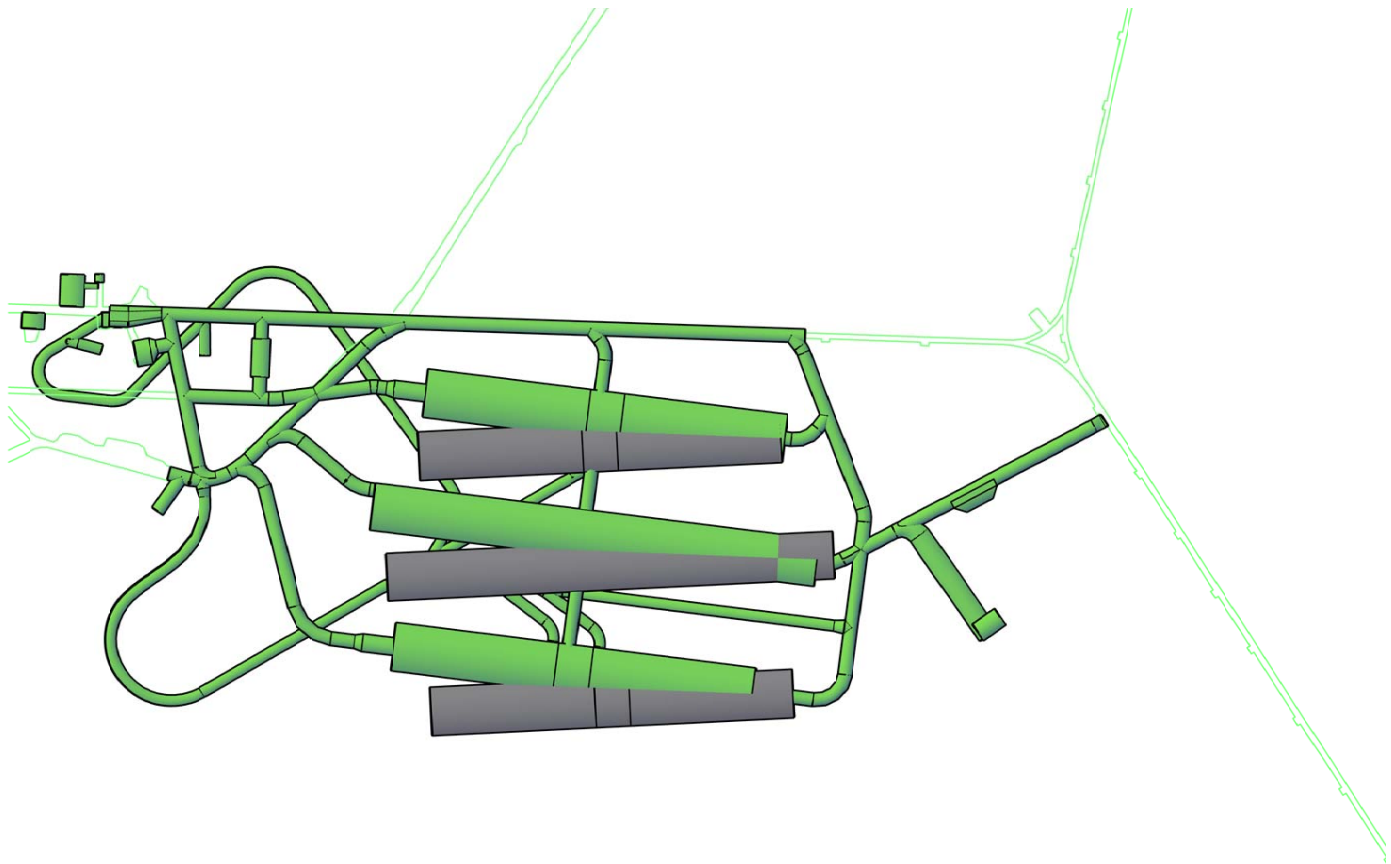
For $g > 2p$ we want the conversion to be outside box

Fraction of events in the vertical plane.

- Assume vertical is defined by 3 mm width.
- Fraction of two track events in the vertical plane as a function of gap length will be $\sim 0.3\text{cm}/\text{gap} < 0.2$.
- Estimate that the number of golden events is $\sim 10\text{-}20\%$. About 20% of these might be affected.
- For multi-track shower events, the situation gets worse since each shower has a $\sim 10\text{-}20\%$ chance of being in the vertical plane.
- For 2-3 GeV neutrinos Maxim's number is $\sim 9\%$ for electrons and $\sim 4\%$ for photons. We are working on this.

Solutions ?

- Need to get better estimates of the problem from generator level simulations.
- Cannot eliminate the problem and so try to reduce it for the golden events only.
- Golden events have forward-going single leptons or showers with low multiplicity.
 - Put an angle between beam and vertical plane.
 - Either tilt the plane or rotate the cavern.
 - Adjust the collection field as a function of height ?



cartoon shows what rotating the caverns 10 degrees would look like in gray as compared to the current layout in green. Aside from the obvious need to redesign all accesses, a few comments:

The west end of the south cavern moves into a less known rock mass (outside of the area where we drilled)

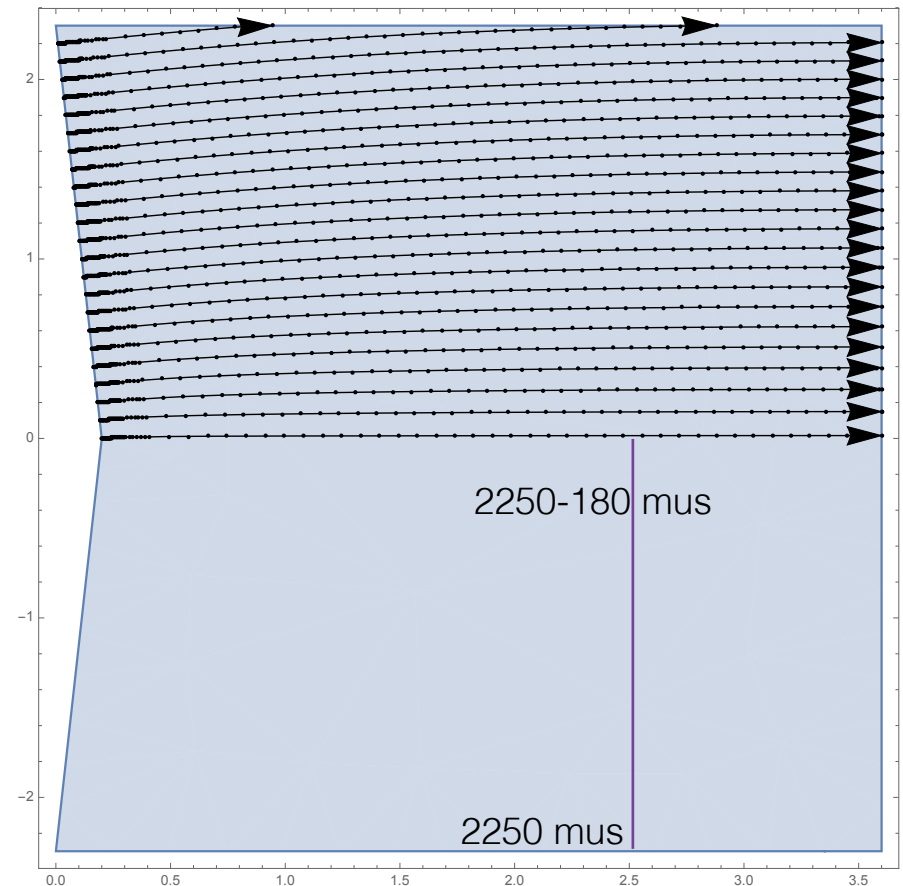
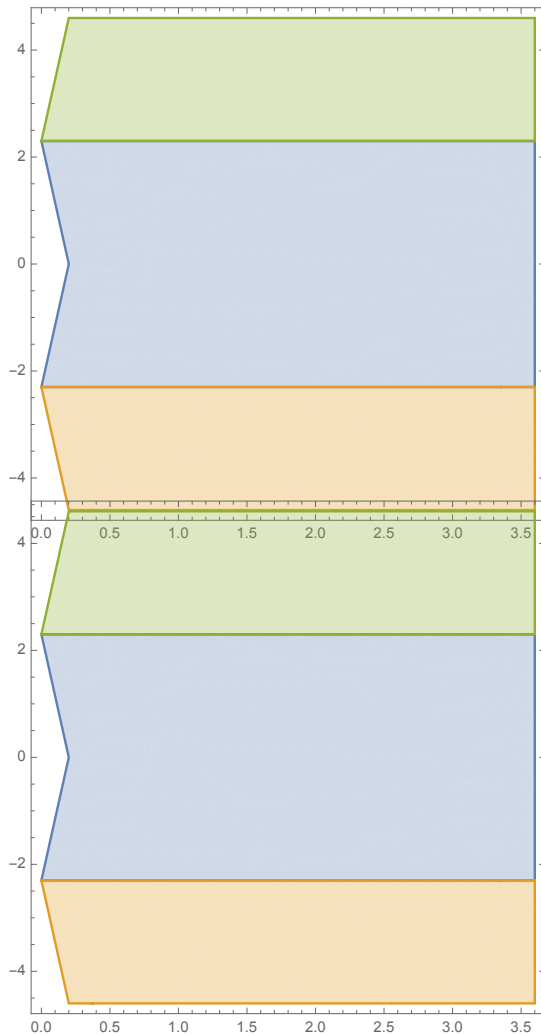
2. The distance into the south cavern increases, increasing cost

3. this might be slightly favorable geotechnically based on foliation orientation.

4. The turning radius coming into both ends would be slightly easier to achieve, primarily because the west end gets further away, giving more space to turn.

appears to be technically feasible.

How about APA angle ?



Issues and priorities

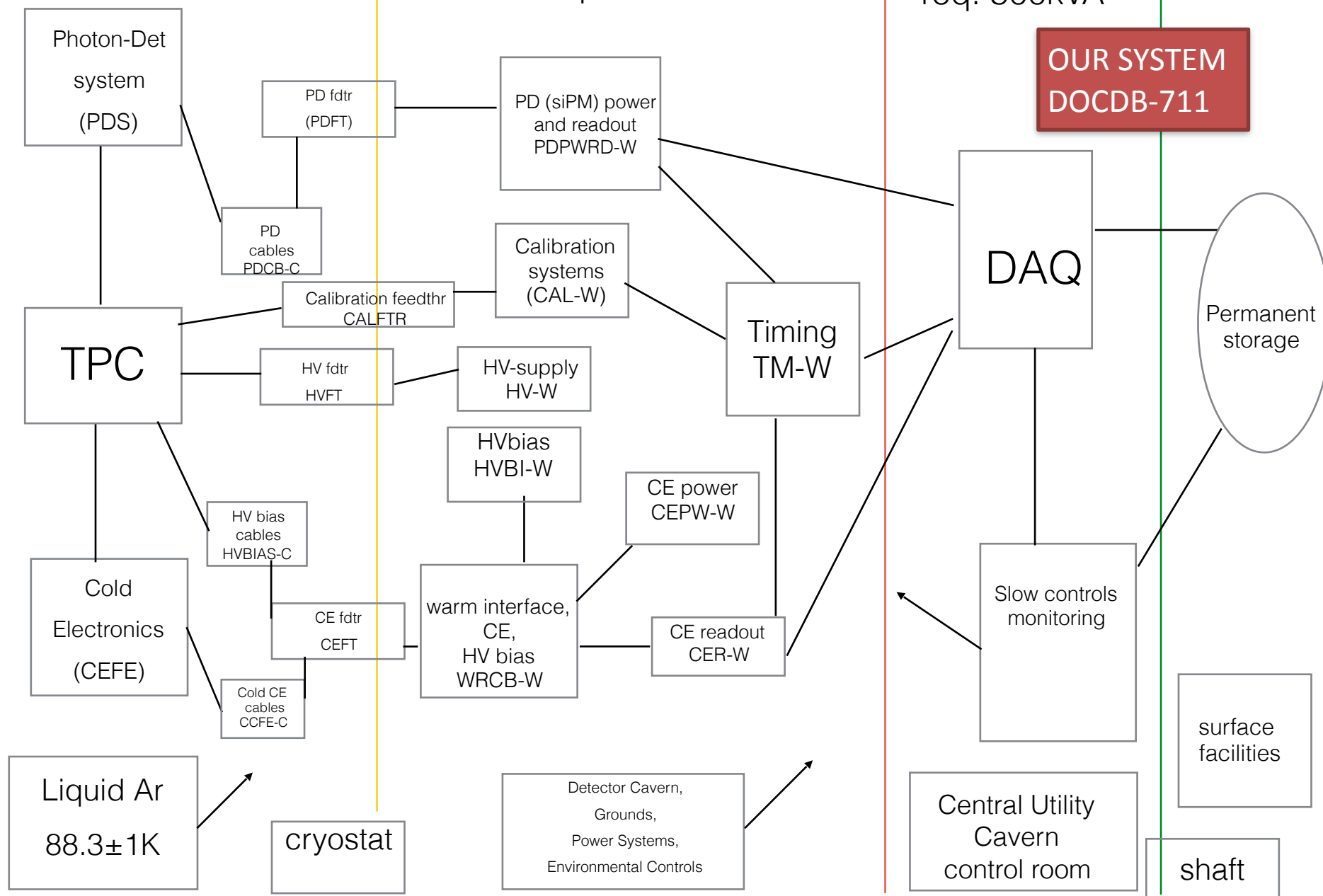
- Will calibration become more difficult ? Yes ?
- Does geometry of the APA in the corners need to be changed to parallelogram ?
- There will be issues with transparency condition and the field inside has to be raised to match the greater field.
- Recombination will be different in different regions of the detector causing charge and light emission calibration to vary.
- Track length will depend on the drift time. It is not a large effect.
- The region of ambiguity will be changed to another tilted region.
- The reconstruction will become more complicated for complex events.

Electronics (10kton)
heat load 24 kW (total 70kW)

<400kW (for 10 kton)
req: 500 kVA

<500kW (total)
req: 500kVA

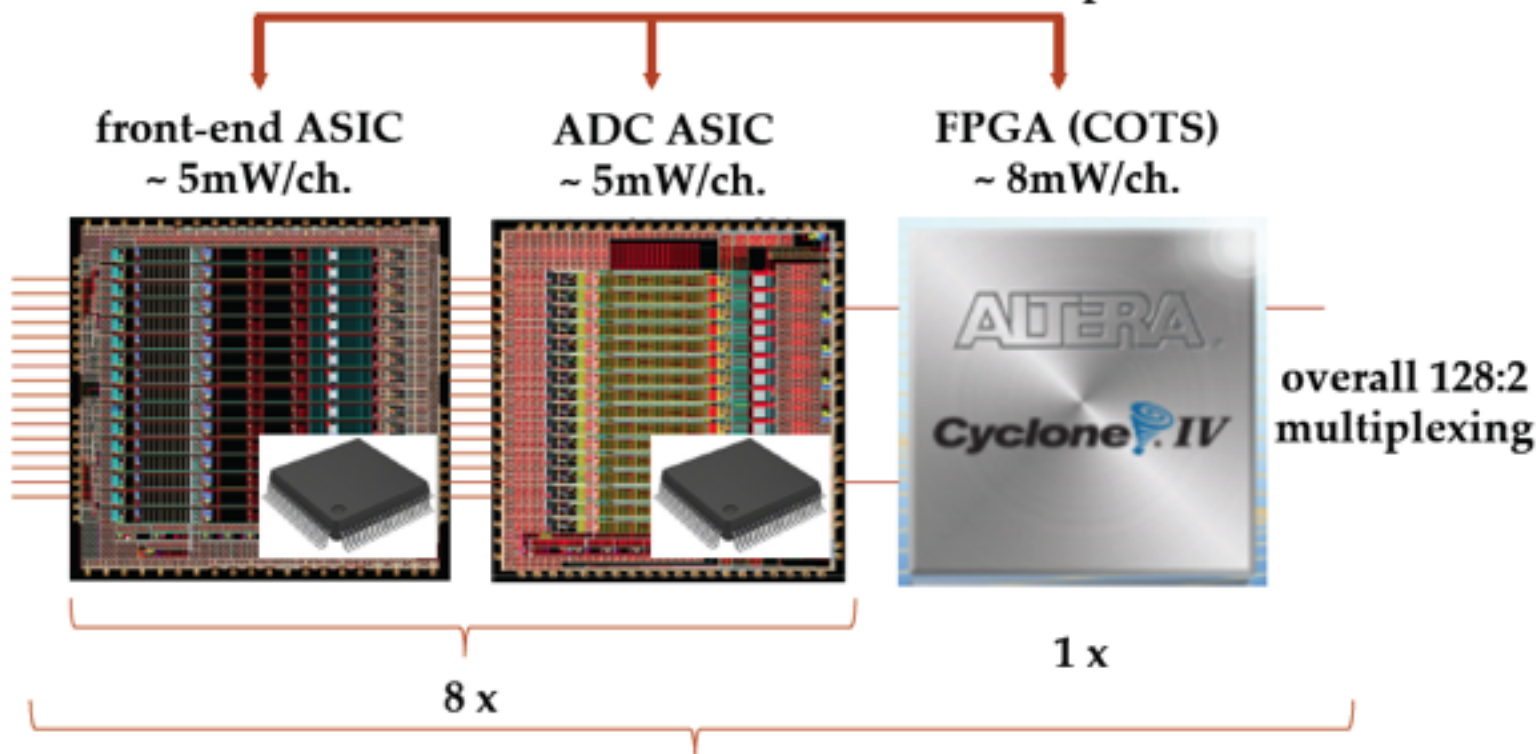
??kW



Cold Electronics



voltage regulation
(COTS)
($< 100\text{mV}$ dropout)



*A Complete Front
End Readout Chain*



front-end cold
module
serving 128 wires
 $\sim 2.4\text{ W}$

2015/01/12

This is going into extensive testing and prototyping now.

Conclusions

- **The most important physics requirement is the need to reconstruct multi-track events with >80% efficiency and measure their energy.**
- This has not been demonstrated yet. There are two major geometric issues:
 - The forward-going nature of high energy beam events cause ambiguities in pattern recognition.
 - Tracks going towards the wire plane have poor resolution on the induction plane.
- Other issues are
 - What fraction of energy is in multiple protons and neutrons that emerge from vertex and how to correct it.
 - What is the effect of signal to noise on e/gamma separation
- Following parameters must be examined with high priority:
 - What fraction of golden events are affected by vertical ambiguity.
 - What is the optimum tiling pattern for wires (or wire cells) for
 - reconstruction
 - charge resolution
 - What are the physics requirements on electronics performance ! THIS NEEDS HUGE AMOUNT OF WORK.
 - What is the optimum APA dimension ? This is coupled to wire angle, wire length, and any potential intentional distortion.
 - What is the optimum angle for neutrino beam to allow maximum efficiency for golden events.